THE ASTROPHYSICAL JOURNAL, 185:L41–L45, 1973 October 1

ON THE NATURE OF THE IONIZING AGENTS OF THE INTERSTELLAR MEDIUM

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Received 1973 July 23

ABSTRACT

The ionization structure of the interstellar trace elements predicted by the steady-state cosmic-ray, X-ray, and ultraviolet star ionization models, even when allowance is made for the stellar H II region, is in disagreement with satellite observations of at least two stars. The conclusion is reached that, in some regions of the Galaxy, the flux of cosmic rays or X-rays is much smaller than was thought previously.
Subject headings: cosmic rays — interstellar matter — spectra, ultraviolet — X-rays

The recent determination of the state of ionization of the trace elements in the interstellar gas, by means of the ultraviolet satellite *Copernicus,* provides a very sensitive way of discriminating between different theories of the heating and ionization of the interstellar medium. The predicted distribution of the trace elements among the different ionization stages can be compared with the *Copernicus* data on unreddened stars (Rogerson *et al.* 1973) since in the intercloud medium (to which these observations refer, presumably) we expect complications arising from opacity effects, grain presence, etc., to be minimized. This comparison has been made for the ultraviolet star ionization model (Mészáros 1973*a*), and for ionization by 2-MeV cosmic rays, by 0.1-keV X-rays, and the observed X-ray background (Weisheit 1973). The results of this comparison (Rogerson *et al.*) indicated that all four theories predicted results incompatible with at least some of the stars observed, but the comparison was made uncertain because of the possible effect that the star's own H II region might have on the line-of-sight densities. However, the effect of stellar H II regions has been recently calculated (Mészáros 1973*b*), and this difficulty can now be obviated. In this *Letter* we present calculations that allow for the H II regions, and that provide strong evidence against cosmic-ray, X-ray, or hard-ultraviolet photon ionization, in the direction of at least two stars.

The main problem in interpreting the observations, aside from the presence of H II regions, is the lack of information on the velocity dispersion of the stronger lines. Thus, for instance, in the data of Rogerson *et al.* the column densities of C II, N II, and others is not directly available unless one assumes the value of b, the velocity dispersion factor. In the *Copernicus* papers, values ranging between 4 and 10 km s^{-1} were considered for b, which is probably a safe range. However, the weaker lines, such as C I, N I, and C III, among others, have smaller column densities and are more insensitive to the adopted b-value. The intrinsic experimental errors in *Copernicus* amount to approximately $\pm$ 10 percent in the equivalent-width measurements, and thus it would seem that the column densities of C I, N I, C III, and the absence of N III, are the quantities about which one can have the most confidence. It would appear useful, therefore, to base any theoretical conclusions on arguments involving mostly these relatively secure quantities.

The star with the most line information available is λ Sco, where both interstellar C I and C III are measured. N I is measured also, but not N III (the identifications of N III given in the *Copernicus* papers are now believed to be spurious, at least in three of the four unreddened stars (e.g., York 1973). Consider the hypothetical situation in which the gas density around the star is large enough that the star is surrounded by an H II region whose contribution to the line of sight is nonnegligible. Knowing the spectral type, it is possible to compute the amount of C I column density in the H II region. Since C I ionizes at 11.26 eV, below the hydrogen threshold, it is easy to show that in the Strömgren sphere (C I/C II) $\lesssim 3 \times 10^{-5}$, for a uniform density $n_{\mathrm{H}} > 10$. The amount of C I computed in the H II region is $N(\mathrm{C\,I}) < 4 \times 10^{11}$ cm^{-2}, much less than that measured in λ Sco, $N(\mathrm{C\,I}) = 3.16 \times 10^{13}$ cm^{-2} (this is the amount for $b = 6$ km s^{-1}; for $b = 4$ it is 3.4×10^{13} and for $b = 10$ it is 3×10^{13}), and therefore all the C I measured has to be outside the H II region. This gas outside the H II region is presumably intercloud gas, since the reddening is so small ($E_{B-V} < 0.03$), and the neutral hydrogen column density measured by means of Lα, $N_{\mathrm{H}} = 7 \times 10^{19}$, corresponds at the star's distance of 110 pc to a volume density $n(\mathrm{H\,I}) = 0.2$ cm^{-3}. Typical values for the temperature, under these circumstances, are $T = 10^4$ ° K, and for the electron density $n_e = 10^{-2}$–10^{-1} cm^{-3} (Dalgarno and McCray 1972). C I will be ionized by the diffuse near-ultraviolet background flux of stellar origin. The value for the ionization rate, based on Habing's flux, is (Weisheit 1973).

$$\zeta_{\mathrm{C\,I}} = 1.7 \times 10^{-10}\ \mathrm{s}^{-1}. \quad (1)$$

The cross-section for ionizing C I is well known, and the flux is an experimentally measured quantity. A recent redetermination of this flux (Witt and Johnson 1973) gives a value in the range of interest which is a factor of 2 higher, because of a different way of treating the effect of the extinction from grains. This, however, is not a large difference, and it is doubtful that the rate (1) could be in error by much more than a factor of 2. According to Habing (1968), the flux could be at most a factor of 3 higher inside associations, and hardly ever fall below 40 percent of the mean. In the presence of such a diffuse, steady flux, the ratio of C I/C II in the intercloud medium is given by the ionization equilibrium equation

$$N(\mathrm{C\,I})/N(\mathrm{C\,II}) = \alpha_{\mathrm{C\,I}} n_e \zeta_{\mathrm{C\,I}}^{-1}, \quad (2)$$

where $\alpha_{\mathrm{C\,I}}$ is the radiative recombination rate for the process C II + $e^- \rightarrow$ C I. For a temperature of 10^4 ° K, the value of $\alpha_{\mathrm{C\,I}}$ can be computed from Tarter's (1971, 1973) expressions, and comes out to be $\alpha_{\mathrm{C\,I}} = 4.5 \times 10^{13}$ cm^3 s^{-1}. For $n_e = 10^{-2}$–10^{-1}, the ratio in equation (2) is 2.6×10^{-5}–2.6×10^{-4}, and since this equation refers to material outside the H II region, where $N(\mathrm{C\,I})_i = 3 \times 10^{-13}$, we see that in the same region $N(\mathrm{C\,II})_i = 10^{17}$–$10^{16}$, where the suffix i identifies strictly interstellar quantities. This amount of calculated interstellar C II is comparable to the observed quantity (1.9×10^{16} at $b = 6$), and it should be a relatively secure quantity, since all the numbers entering equation (2) are relatively secure.

The next step now involves the actual ionizing agents under scrutiny, since to ionize the interstellar hydrogen, C II, or any other ion with ionization potention $\chi > 13.6$ eV, we need the 2-MeV cosmic, X-rays, hard-ultraviolet photons, or any other mechanism that is capable of explaining the hydrogen ionization fraction. According to Hughes, Thompson, and Colvin (1971), the hydrogen and free-free absorption observations can be explained if the total mean ionization rate of hydrogen is $\zeta_{\mathrm{H}} = 2 \times 10^{-15}$ s^{-1}. We consider now the different models individually.

a) *2-MeV cosmic-ray ionization.*—For these, the total ionization rate (primary and secondary) requires a primary ionization rate of $\zeta_{\mathrm{H,CR}} = 1.2 \times 10^{-15}$ s^{-1} (using the formulae of Field, Goldsmith, and Habing 1969, or Spitzer and Tomasko 1968). Some authors (e.g., Silk 1973) have argued for higher values of ζ_H in the intercloud medium, while others (e.g., Glassgold and Langer 1973) have presented evidence for a lower value, at least in clouds. For the present, we shall adopt 1.2×10^{-15} s^{-1}. Now the ionization rate of a particular subshell J of a trace ion i containing g_i electrons with binding energy U_J can be written as (Garcia, Gerjuoy, and Welker 1968; Weisheit 1973)

$$\zeta_i^J = g_i^J\,(13.6/U_J)\zeta_H. \tag{3}$$

Using the binding energies of Davidson (1970) and the Auger effect formalism of Weisheit (1973), one can obtain the effective (Auger corrected) ionization rate of C II by cosmic rays, $\zeta^{\rm eff}{}_{\rm C\,II,CR}$. The correction, in this case, is negligible, and $\zeta^{\rm eff}{}_{\rm C\,II,CR} \simeq \zeta^{K+L}{}_{\rm C\,II,CR} = 1.65 \times 10^{-15}$ s^{-1}. The equilibrium abundance of C III outside the H II region is given by

$$N(\text{C II})/N(\text{C III}) = \alpha_{\rm C\,II}\, n_e(\zeta^{\rm eff}{}_{\rm C\,II,CR})^{-1}. \tag{4}$$

Again from Tarter's data, $\alpha_{\rm C\,II} = 2.7 \times 10^{-12}$ at $T = 10^4$, and for $n_e = 10^{-2}$–10^{-1} as before, corresponding to $N(\text{C II})_i = 10^{17}$–$10^{16}$, we deduce from the above ionization equilibrium equation that $N(\text{C III})_i = 6 \times 10^{15}$–$6 \times 10^{13}$, instead of the observed value 9.6×10^{11}, i.e., cosmic rays predict at least a factor 60 more C III than is observed. Since this is all interstellar C III, and the H II region would also be expected to contribute C III, the discrepancy should actually be even larger.

b) *0.1-keV X-ray ionization.*—In this model, to the observed diffuse X-ray background (which in itself is insufficient to provide the necessary ionization rate of hydrogen), an injection spectrum of 0.1-keV X-rays is added, to make up $\zeta_H = 2 \times 10^{-15}$ s^{-1}. For these, according to Werner, Silk, and Rees (1970), the total hydrogen ionization rate of 2×10^{-15} s^{-1} corresponds to a primary hydrogen ionization rate of $\zeta_{\rm H,XR} = 7.7 \times 10^{-16}$ s^{-1}. From Weisheit's formulae, we find that the Auger term is negligible and $\zeta^{\rm eff}{}_{\rm C\,II,XR} \simeq \zeta^{K+L}{}_{\rm C\,II,XR} = 3.5 \times 10^{-14}$ s^{-1}. Using again an equation like (4), and $\alpha_{\rm C\,II} = 2.7 \times 10^{-12}$, we deduce that the amount of strictly interstellar C III predicted is 1.3×10^{17}–1.3×10^{15} cm^{-2}, i.e., 0.1-keV X-rays predict at least 1300 times too much C III.

c) *Observed soft X-ray background.*—If the flux values of McCray and Dalgarno are extended down to 0.1 keV and if Weisheit's (1973) cross-section for C II is used, a value $\zeta_{\rm C\,II} = 4.4 \times 10^{-16}$ s^{-1} is obtained. The same argument as above gives $N(\text{C III})_i = 1.6 \times 10^{15}$–$1.6 \times 10^{13}$, so the X-ray observed background predicts at least 16 times too much C III. An added discomfiture is that this source of radiation only gives rise to a $\zeta_H \simeq 10^{-17}$ s^{-1}, hence an extra ionizing agent is required to explain the hydrogen ionization.

d) *Ultraviolet stars with* $T_{\rm eff} = 150{,}000°$ K.—This case has been analyzed by Mészáros (1973). The deduced C II ionization rate is $\zeta_{\rm C\,II} = 3 \times 10^{-13}$–$2 \times 10^{-15}$ s^{-1} for a range of baryon densities $n_0 = 3 \times 10^{-2}$–1 cm^{-3}, and $n_e = 3 \times 10^{-2}$ cm^{-3}. The predicted C III is again unacceptably high, $N(\text{C III}) = 5 \times 10^{17}$–$9 \times 10^{14}$.

We see, therefore, that, even allowing for stellar H II regions, none of the four models discussed is able to reproduce the observations in λ Sco. One cannot argue that an increased n_e could solve things, since then to keep up such a high electron density in a steady state model, ζ_H must be made also larger. The only way to have a higher electron density without a correspondingly higher ζ_H is in flashionization models, i.e., time-dependent schemes. (We briefly comment on this possibility below.)

The same set of arguments on the carbon abundances cannot be made for the other three unreddened stars observed by *Copernicus,* because the C I abundance was below the noise level. However, N I is observed in all four stars, and N III is (contrary to the published report, see above) now believed to be below the noise level in λ Sco, υ Sco, and α Leo, while α Eri needs to be reobserved, but probably shows the same phenomenon. Therefore, one can attempt to build an argument similar to that for λ Sco, but involving N I, N II, and the new upper limit on N(N III) $\lesssim 10^{12}$ cm^{-2}. Without going into details of our calculation, we quote the final result for the star α Leo (we have not attempted this on υ Sco, since here some additional assumptions would be required). Assuming all the N I column density to be outside the H II region, the derived N(N III)$_i$ (strictly interstellar) is 3.2×10^{13}, if the nitrogen-to-hydrogen ratio is solar, and 4.7×10^{12}, if nitrogen is depleted by a factor of 5. As one would expect the H II region to contribute also some N III, the predicted value of N(N III) is at least a factor 5 more than the observed upper limit. This, admittedly, is not such a strong discrepancy as for the carbon abundances in λ Sco, but it is in the same direction. The same analysis on α Leo with 0.1-keV X-rays leads to larger discrepancies, which practically rule out this possibility, and although the case against cosmic rays here is weak, it does lend support to our interpretation of λ Sco, where the case appears to be strong. Thus, as new observations are in progress which may shed light on the situation, it seems important to emphasize that the problem deserves a careful analysis, since from the above arguments, mainly on λ Sco, one would seem to reach the conclusions that either (a) a revision of the steady-state cosmic-ray or X-ray heating theories is needed, (b) an explanation would be required of why, if these theories were correct, they do not apply to the particular regions under consideration, or (c) a new physical agent for producing the ionization may be necessary.

The first possibility, at present, consists mainly in the time-dependent supernova-heating type of theory. Since this theory requires soft X-ray emission, 100 eV $< h\nu <$ 200 eV, it is hard to see how these bursts would avoid producing significant amounts of N III, C III, and higher ions. Nonresonant charge-exchange effects could conceivably be invoked also, but as of yet their effectiveness is a matter of controversy. The second possibility could perhaps involve the existence of a strong magnetic field, shielding the Scorpius association from 2-MeV protons, or perhaps the stellar wind of the association stars might be strong enough to deflect the cosmic rays. This is mere conjecture at present, and a quantitative analysis would be required. Furthermore, it remains to be seen whether other stars, not belonging to associations, need invoke the same mechanism. From preliminary *Copernicus* results, it would appear that several other stars also show the lack of N III. The last possibility—namely, that other physical agents may be responsible for the bulk of the ionization—is at present under investigation, and the results of a model involving ultraviolet photons ($h\nu <$ 24.58 eV) will be published separately (Mészáros 1973b).

In conclusion, one region of the sky appears to indicate a flux of hard ionizing (2-MeV cosmic rays, X-rays) which is at least two orders of magnitude smaller than was previously thought. That a small amount of hard radiation might be present is suggested by the observation of small amounts of O VI and, in some reddened stars, of Si IV (Morton *et al.* 1973), although some of this could be due to the observed diffuse X-ray background. But for λ Sco, at least, a strong case can be made against cosmic rays or X-rays providing the bulk of the ionization, and a similar argument on α Leo seems to support this conclusion.

Thanks are due to Lyman Spitzer, Jr., George B. Field, and Joseph Silk for interesting discussions on the subject, and also to the organizers and participants of the 1973 Aspen Center for Physics Workshop on the Interstellar Medium. Support through National Aeronautics and Space Administration grant NGL-31-001-007 is gratefully acknowledged.

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